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Observed climate variability over Chad using multiple observational and reanalysis datasets

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ABSTRACT

Chad is the largest of Africa's landlocked countries and one of the least studied region of the African continent. The major portion of Chad lies in the Sahel region, which is known for its rapid climate change. In this study, multiple observational datasets are analyzed from 1950 to 2014, in order to examine the trend of precipitation and temperature along with their variability over Chad to understand possible impacts of climate change over this region. Trend analysis of the climatic fields has been carried out using Mann-Kendall test. The precipitation over Chad is mostly contributed during summer by West African Monsoon, with maximum northward limit of 18° N. The Atlantic Ocean as well as the Mediterranean Sea are the major source of moisture for the summer rainfall over Chad. Based on the rainfall time series, the entire study period has been divided in to wet (1950 to 1965), dry (1966 to 1990) and recovery period (1991 to 2014). The rainfall has decreased drastically for almost 3 decades during the dry period resulted into various drought years. The temperature increases at a rate of 0.15 °C/decade during the entire period of analysis. The seasonal rainfall as well as temperature plays a major role in the change of land use/cover. The decrease of monsoon rainfall during the dry period reduces the C4 cover drastically; this reduction of C4 grass cover leads to increase of C3 grass cover. The slow revival of rainfall is still not good enough for the increase of shrub cover but it favors the gradual reduction of bare land over Chad.

1. Introduction

Africa is the second largest continent as well as the second populous place of the world. Because of its vastness, Africa incorporates eight different climatic zones according to Koppen climate classification system (Köppen, 2011, 1884; Rubel and Kottek, 2011). These includes the desert, arid regions in the north, rain forest in the south, cross-savanna in the central region and many more. All these climate zones in Africa are particularly vulnerable or sensitive to climate variability and climate change (Olago and Odada, 2005). One of the interesting geographical features of Africa is its position with respect to the equator, which almost divides Africa into two halves such as the northern and southern part, which have their own climatic influences.

The regional climate analysis over Africa shows that 2013 was the warmest year on the African continent (IPCC, 2013) with the observed temperature much higher as compared to the average of 1961 to 1990 in most part of Africa. Another report from World Meteorological Organisation (WMO) on global climate shows that, 2011 to 2015 is the warmest period for all continents except for Africa. More recently, WMO confirms 2016 as the hottest year on record, about 1.1 °C above pre-industrial era. The warming of climate system was unequivocal since 1850 (IPCC, 2007), which reported that the increase in global temperature is 0.75 °C from the period between 1850–1899 to 2001–2005 (Trenberth et al., 2007). All these reports clearly indicate the rise of temperature along the African continent with a positive temperature trend. In terms of precipitation, there exists a large regional variability within Africa (IPCC, 2007). However, the largest negative trend in annual precipitation is observed over western Africa and the Sahel region whereas a drying trend is also evident over southern Africa since 1901 (Trenberth et al., 2007). Rainfall over the Sahel region of western and central Africa was generally close to or above normal during the period 2011 to 2015, except in 2011.

Several studies have been carried out over Africa to understand the climatic variability of temperature, such as the increasing warming (Collins, 2011; Hulme et al., 2001); coherent warming of both maximum and minimum temperature especially during winter (Caesar et al., 2006); gradual decrease of cold climate extreme during the second half of 20th century (Frich et al., 2002; New et al., 2006) and

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increase of extreme hot days and nights (New et al., 2006). In addition, various studies try to find the behavior of rainfall over African continent. The oscillatory behavior of rainfall (Ogallo, 1979) and climate extremes (New et al., 2006) without any particular trend have been reported. The decrease of rainfall over Sahel region after 1970 is reported using long-term rain gauge data (Le Barbé et al., 2002). Most of the years during 1950s (1970s) are found to be wet (dry) years (Nicholson, 2000, 2001). They further analyzed the land surface-atmospheric interaction to understand the interannual variability of rainfall and found that the recovery from the dry state to normal is slower than the wet state and hence the dry condition persist over Sahel region of Africa. The inter-decadal variability of rainfall over Sahel region along with a relatively rainfall stable period is observed during 1961 to 1990 (Hulme et al., 2001). Several regional climate analyses were also conducted over specific zones; for e.g. study of the rainfall variability over southern and west Africa does not show any statistical significance (New et al., 2006); whereas the rainfall extremes have increased over the eastern part of south Africa (Kruger, 2006) and the warming/cooling over the western Indian Ocean modulates the rainfall over Namibia and south Africa (Landman and Mason, 1999). Rowell et al. (1995) represents the global SST pattern and its influence on rainfall variability over northern Africa or over semi-arid region of west Africa (Nicholson, 2000, 2001).

Some earlier studies depicts that there is no trend in annual rainfall over Africa (Bunting, 1975; Landsberg, 1975; Rodhe and Virji, 1976) during the period 1935 to 1975. Four years later, Ogallo (1979) reported that there is no significant trend in rainfall over Africa for the same period however, they have also mentioned that most of the annual rainfall series indicated an oscillatory characteristics except over 4 stations where increase in rainfall pattern is observed and that have been attributed to the local factors. In contrast, IPCC indicates a clear change in rainfall trends (IPCC, 2007). In terms of temperature, a significant increasing trend over all of Africa and its sub-regions (such as northern Hemisphere Africa, southern Hemisphere Africa, tropical Africa, and subtropical Africa) is reported (Collins, 2011). They found both northern and southern parts of Africa have a significant warming during summer in the most recent period 1995 to 2010 as compared to the earlier period 1979 to 1994. However, during winter, the significant warming is only concentrated over north of Africa. The comparison of the two most recent decades depicts that the warming is observed over the above-mentioned regions during 2001 to 2010 as compared to 1979 to 1990. Many studies focus to understand more precisely the inter-seasonal variability of the west African monsoon (N'Datchoh et al., 2017; Paxian et al., 2016; Poan et al., 2016; Roehrig et al., 2013) because of its huge socio-economic impacts on local populations. Few researches are dedicated to identify dust sources in the Namibia desert (Eckardt and Kuring, 2005) or in Bodélé depression (Washington et al., 2006) and their implications to climate change, shifting of ITCZ and its impact on rainfall in Sahel and even more aspects of climate. As mentioned earlier, each climate zone will have their own peculiar/signature response to the climate change. For this purpose, it is very necessary to provide the details about each regions of Africa. Further studies over different sub-regions of Africa will be helpful to get an idea about the change in temperature and precipitation trends over these sub-regions. This information will be an important contribution to make strategy for water resource management (both collection and storage), seasonal agriculture and food production to counter the ill effects of climate change by proper adaptation mechanism, sustainable development of different sub-regions.

Although several studies have been conducted over the Sahel region, the study of climate variability over some countries like Chad have either least or no focus in the past. The major earlier climatic studies over Chad involve the Saharan dust in north and change in micro-climate due to the presence of Lake-Chad (Bastola and François, 2012; Coe and Foley, 2001; Delclaux et al., 2008; Nilsson et al., 2016). Therefore, this study aims to examine

- the under-focused climate variability over Chad from 1950 to 2014.
- the changes in temperature and precipitation pattern and their trend within the study period.
- the changes in land use/land cover (hereafter, LULC) with special focus on C3 and C4 type of grass covers.

These analyses will provide an indication of changing climate patterns over Chad, which may form basis for other studies on future climate change. The change in LULC will further induce changes in ecological systems (biogeochemistry of ecosystems, nitrogen and carbon cycles), animal productivity and agronomic output. In addition, the change in temperature/precipitation and land LULC will have its socio-economic impact on the country. These impacts of slowly changing climate in this study would help for developing mitigation and adaptation strategies. Below, Section 2 deals with the datasets used and methodology adopted for this study. Section 3 discusses about the geographical location and LULC pattern over Chad. Section 4 describes the results and discussion while Section 5 summarizes the main findings followed by the concluding remarks.

2. Data and methodology

Multiple monthly datasets are used for the analysis of spatial pattern of seasonal and annual climatology of various meteorological parameters over Chad from 1950 to 2014, listed below

- University of Delaware (hereafter, UDEL) at 0.5° × 0.5° horizontal resolution for the analysis of temperature and precipitation (Willmott et al., 2001).
- Climate Research Unit (hereafter, CRU) at 0.5° × 0.5° horizontal resolution for the analysis of temperature and precipitation (Harris et al., 2014).
- Global Precipitation Climatology Center (hereafter, GPCC) at 0.5° × 0.5° horizontal resolution for the analysis of precipitation (Schneider et al., 2011).
- National Center of Environmental Protection (hereafter, NCEP) at 1.5° × 1.5° horizontal resolution for the analysis temperature and vertically integrated moisture flux and transport (Kalnay et al., 1996).
- LULC data (developed by Meiyappan and Jain) at 0.5° × 0.5° horizontal resolution for the analysis of land use and land cover change (Meiyappan and Jain, 2012).
- United State Geological Survey Global Land Cover Characterization (hereafter, USGS GLCC) at 0.5° × 0.5° horizontal resolution for the analysis of topography (Brown et al., 1999).

The study has been conducted for 65 years ranging from 1950 to 2014, in order to understand the mean behavior of these meteorological parameters and their trends over Chad. The area-averaged temperature over Chad (the grid points lie within the political boundary of Chad) is considered for the present analysis. It is observed that the rainfall over Chad is not uniform; the northern part of the country does not receive rainfall throughout the year as it belongs to the great Sahara Desert. The area-averaged rainfall is computed like the temperature but over a region where longitude ranges from 13.5° E to 24° E and latitude varies from 7.5° N to 16.5° N. The careful removal of grid points over Sahara will provide robust result in terms of rainfall trend and variability over Chad. The standardized precipitation and temperature anomaly is computed by dividing the anomaly (difference of the corresponding seasonal and annual value with respect to long-term seasonal and annual mean) with the corresponding standard deviation value of temperature and rainfall respectively during the period considered for the study. The standardized value greater than +1 (−1) implies the excess (deficit) year in terms of rainfall and warm (cold) year in terms of temperature.

The annual, seasonal (December–February(DJF), Pre-monsoon:

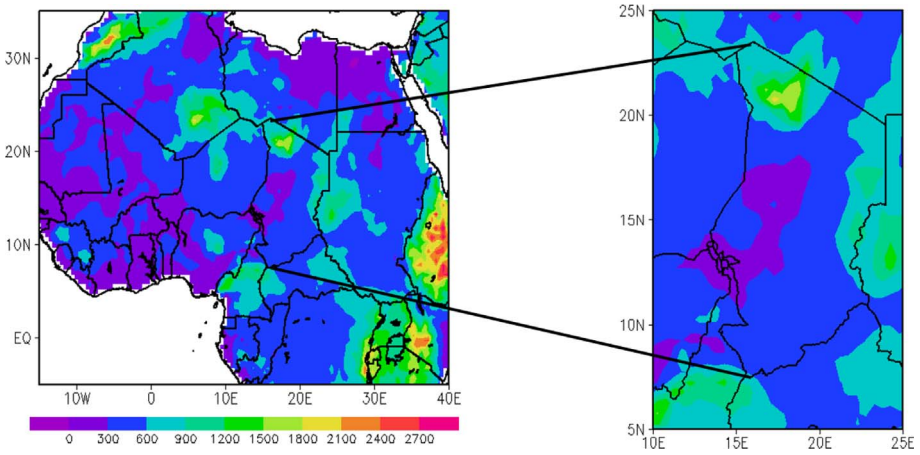

Fig. 1. The location of Chad in Africa; The shaded region is showing the topography (m).

March–May(MAM), Monsoon: June–August(JJA) and Post-monsoon: September–November(SON)) and monthly significance of trend for temperature and precipitation are computed using a non-parametric Mann-Kendall test (MK-test) (Kendall, 1975; Mann, 1945). For determining the slope of the trend, a non-parametric Theil-Sen Sen (1968) slope estimator is used. This test is very useful for cases where the trend may be monotonic and there is no seasonal cycle in datasets. It does not assume a distribution for the residuals and is robust to the

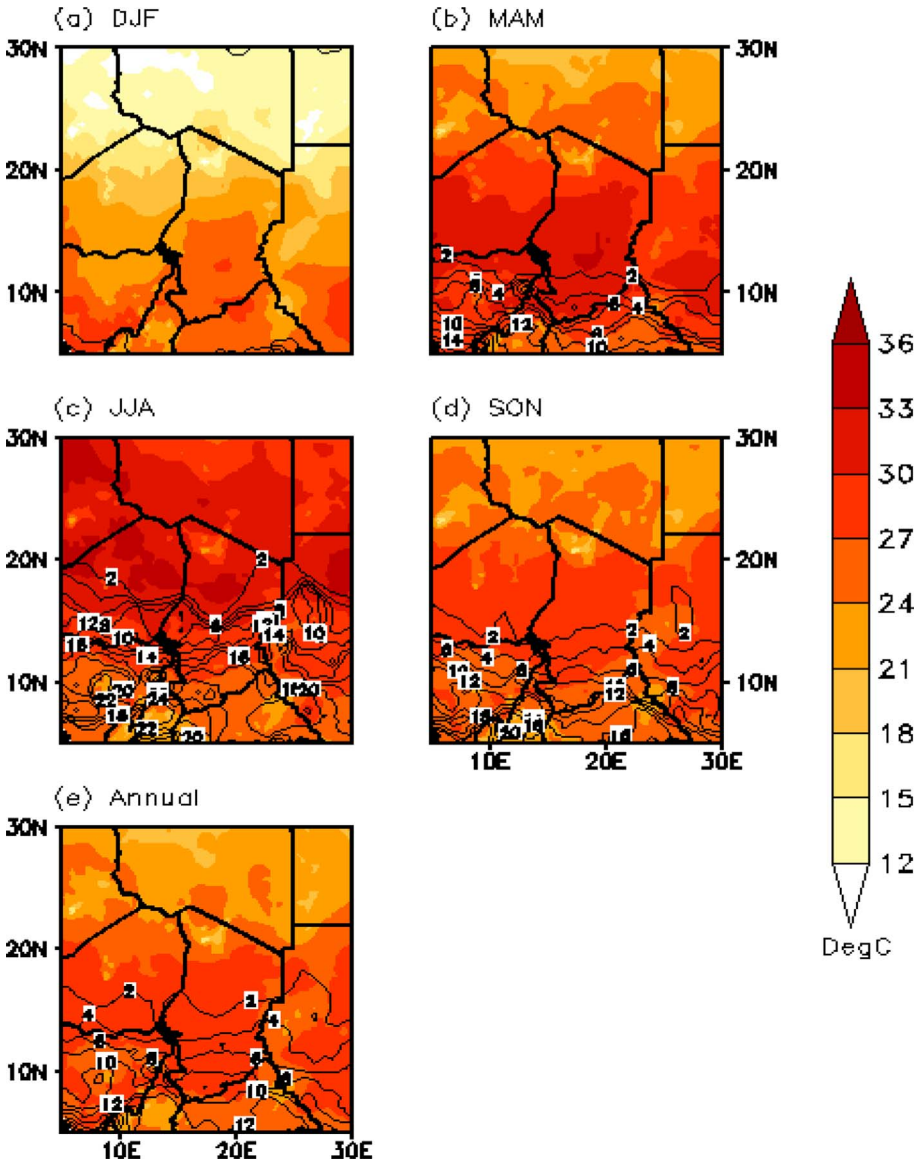

Fig. 2. Climatological rainfall (mm/day: contour) and 2 m air temperature (°C: shaded) obtained from UDEL during JJA, SON, DJF, MAM and annual rainfall for the period 1950–2014.

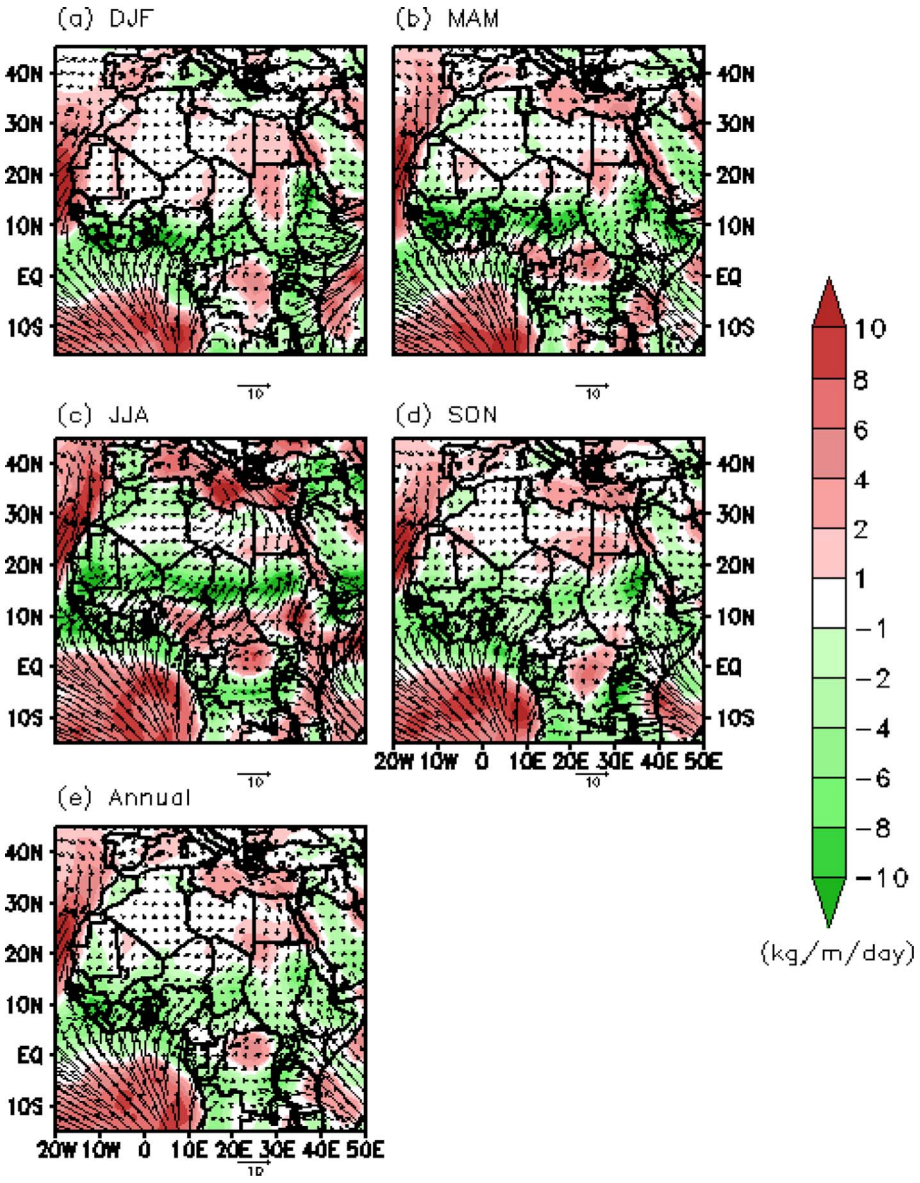

Fig. 3. Climatological vertical integrated moisture flux ($\times 10^{-5}$) and divergence (kg/m/day: in shaded) and transport (in vector) obtained from NCEP/NCAR reanalysis during JJA, SON, DJF, MAM and annual for the period 1950–2014.

effect of outliers in the series. Note that the MK-test is used for testing hypothesis 0 (there is no trend) against 1 (there is a significant tend in the sample dataset). This analysis also helps to figure out the most sensitive seasons and months, which play major roles in determining the annual trends.

3. Geography of Chad

Chad is geographically located in the north central Africa and lies between 7° N to 23° N latitude and 13° E to 24° E longitude. It includes three major climatic regions such as desert, semi-arid and savanna in the north, central and south part of the country respectively. The northern part of Chad is occupied by the great Sahara Desert whereas the southern part mostly experiences tropical climate. Chad is one of the largest country in central Africa (Fig. 1: Chad in African map) and has the largest land share among the Sahel countries (Kandji et al., 2006). Chad is an agricultural country; where around 70% of total population is engaged in this sector. Major portion of the country is within an altitude of 300 to 600 m above mean sea level. Chad lake is situated at the western part of the central Chad. It experiences four seasons such as north hemisphere winter (DJF), pre-monsoon (MAM), monsoon (JJA) and post-monsoon (SON).

4. Results and discussion

In this section, the climate of Chad has been studied by analyzing the climatic fields in terms of Climatology, Inter-annual variability, Climatic Trends and Observed climate change in the following sub-sections.

4.1. Climatology

To understand the climatology of Chad, the study of rainfall, 2 m air temperature, vertically integrated moisture flux and its transport along with different landuse/landcover are analyzed for the period 1950 to 2014. The above-mentioned parameters have been averaged seasonally and annually (except LULC).

The climatological mean of seasonal and annual rainfall (contour) and temperature (shaded) from UDEL for the period of 1950 to 2014 over Chad is represented (Fig. 2a–e). The northern part of Chad, being a part of the great Sahara Desert, hardly gets rainfall throughout the year. The north hemispheric winter over Chad is normally dry and without rainfall (Fig. 2a). The pre-monsoon rainfall varies from 2 to 4 mm /day and is confined to southern part only (Fig. 2b). Monsoon is the wettest period due to the activity of West African Monsoon (hereafter, WAM);

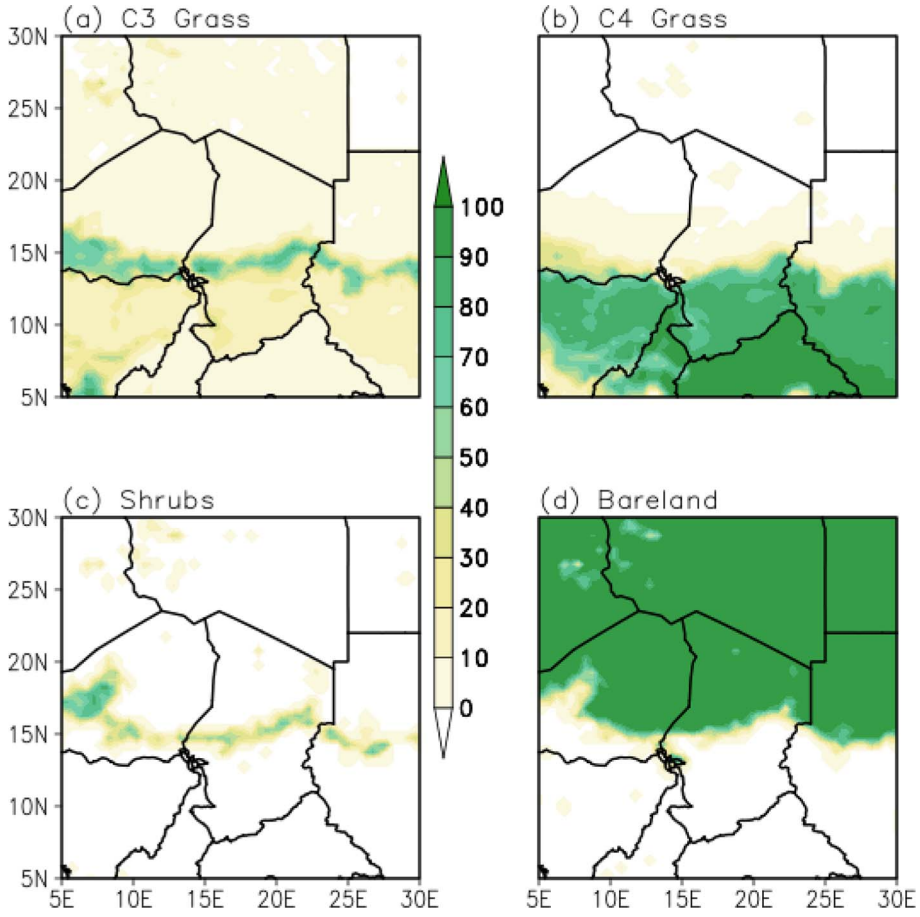

Fig. 4. Climatological annual land cover over Chad (Meiyappan and Jain, 2012) for the period 1950–2014. (a) C3 plants, (b) C4 plants, (c) shrub and (d) bare land.

when the southern and central part of Chad receive maximum rainfall. The higher temperature over Sahara Desert shifts the intertropical convergence zone (ITCZ) towards north during summer (Diallo et al., 2014). With the onset of monsoon, the rain-belt shifts from 5° N to 6° N to 10° N to 12° N during July and August (Diallo et al., 2014; Le Barbé et al., 2002; Sylla et al., 2013; Thorncroft et al., 2011); this jump may also be attributed to the northward shift of the African easterly jet (hereafter, AEJ) (Nicholson, 2000). The rainfall peak near 10° N during summer is maintained by a mid-tropospheric ascend located latitudinally between the cores of AEJ and tropical easterly jet (hereafter, TEJ) that intensify around the onset of monsoon (Diallo et al., 2014). The near surface westerly penetrates up to 15° N limiting the rainfall belt within this latitude (Diallo et al., 2014). The present analysis also confirms that the northern limit of rainfall is around 15° N during JJA (Fig. 2c). The rainfall gradually decreases from south (12 mm /day) to north (2 mm /day) of Chad. Like pre-monsoon, the rainfall activity during post-monsoon is confined to southern part of Chad and ranges from 2 to 6 mm /day (Fig. 2d). It is observed that rainfall during JJA is contributing maximum to the total annual rainfall, hence the annual rainfall pattern is similar to the spatial pattern of JJA (Fig. 2e). The analysis of annual and seasonal rainfall climatology using CRU and GPCC datasets also show similar precipitation pattern over Chad (Supplementary Figs. 1–2).

The careful examination of these plots shows that the observed climatological minimum (maximum) temperature is around 12 °C (> 36 °C) during DJF (JJA) over northern (central) part of Chad. The annual mean temperature is relatively low over south Chad as compared to north Chad. This may be attributed to the higher solar insolation during JJA, which increases the temperature over the desert areas of Chad. During DJF, the southern hemisphere is directly exposed to the longitudinal sunrays, so the diffused incident solar radiation along with radiative cooling over the Sahara Desert reduce the temperature over north Chad. DJF is the coldest season of the year (Fig. 2a); the southern part of Chad remains relatively warmer (24 °C) as compared to northern part (12 °C). The temperature gradually rises from MAM to JJA. During MAM, it varies from 18 to 33 °C while the central Chad experiences the maximum temperature (Fig. 2b). JJA is the hottest season of the year; where temperature greater than 30 °C over most part of the country (Fig. 2c). The spatial distribution of temperature is quite homogeneous during SON and ranges between 27 and 30 °C(Fig. 3d). The annual temperature shows a similar spatial pattern like SON (Fig. 2e). Similar analysis of annual and seasonal 2 m air temperature climatology from CRU and NCEP datasets show comparable spatial pattern of temperature over Chad (Supplementary Figs. 3–4).

The rainfall is mostly linked to the amount of moisture transported from the oceanic part in to the land (Murakami et al., 1984; Pisharoty, 1965; Saha and Bavadekar, 1973) and the moisture feedback from land surface. Therefore, the seasonal and annual analysis of moisture divergence (shaded) and vertically integrated moisture flux and its transport (vectors) is carried out to understand the sources of moisture that contribute to the rainfall over Chad (Fig. 3a–e). The analysis shows that moisture convergence takes place over the southern and central Chad in most of the seasons. The northern part of Chad receives wind from northeast direction known as Harmattan wind (Thorncroft et al., 2011) through out the year. This dry air from the Sahara Desert culminates in less rainfall over northern Chad. During DJF, moisture divergence occurs over Chad resulting in less rainfall (Fig. 3a). During MAM, the northern (southern) part receives dry (moist) air from the Sahara (Atlantic Ocean). This moisture laden air causes rainfall over southern part of Chad (Fig. 3b). Interestingly during JJA, stronger divergence and transport of moisture is observed from Atlantic in south as

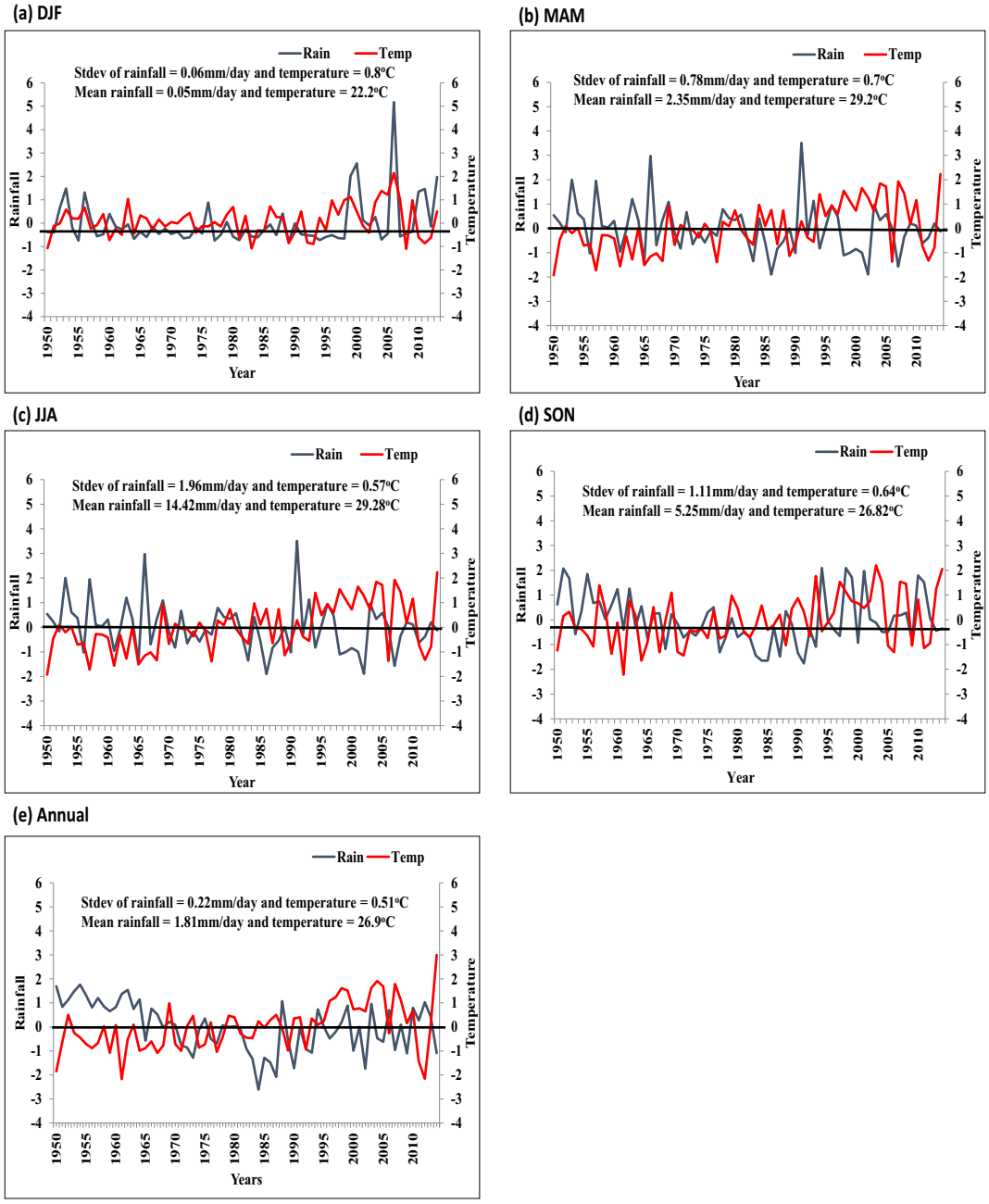
(a) DJF
Rain
Temp
Stdev of rainfall = 0.06mm/day and temperature = 0.8°C
Mean rainfall = 0.05mm/day and temperature = 22.2°C
Rainfall
Temperature
Year
(b) MAM
Stdev of rainfall = 0.78mm/day and temperature = 0.7°C
Mean rainfall = 2.35mm/day and temperature = 29.2°C
(c) JJA
Stdev of rainfall = 1.96mm/day and temperature = 0.57°C
Mean rainfall = 14.42mm/day and temperature = 29.28°C
(d) SON
Stdev of rainfall = 1.11mm/day and temperature = 0.64°C
Mean rainfall = 5.25mm/day and temperature = 26.82°C
(e) Annual
Stdev of rainfall = 0.22mm/day and temperature = 0.51°C
Mean rainfall = 1.81mm/day and temperature = 26.9°C
Years

Fig. 5. Standardized anomalies of precipitation (primary Y-axis, blue) and temperature (secondary Y-axis, red line) during JJA, SON, DJF, MAM and annual for the period 1950–2014 over Chad. The mean and standard deviation of temperature and precipitation are also provided in the plots. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

well as Mediterranean Sea from north towards Chad (Fig. 3c). The stronger convergence of moisture over central and southern Chad causes heavy rainfall and hence rightly the wettest season. During SON, the transport of moisture from Mediterranean weakens and moisture convergence only takes place over southern Chad. This leads to less rainfall, restricted to south of Chad (Fig. 3d). The higher summer temperature creates low pressure over Chad; while the relatively colder oceanic part creates a high pressure zone over Ocean. This pressure difference drags the wind from Ocean towards land points. Hence, the moisture is transported from the area of divergence such as Atlantic and Mediterranean Sea towards Chad. The strength of annual divergence and transport roughly reflects the JJA spatial pattern (Fig. 3e) but with less magnitude.

The climatology of different LULC types such as C3 grass cover, C4 grass cover, shrub and bare-land over Chad are represented (Fig. 4a–d). The hot, sunny and arid climate with temperature range between 32 and 35 °C(generally greater than 22 °C) are favorable condition for the growth of C4 grasses. While, the cool and wet with temperature range 18 to 24 °C(less than 22 °C) are conducive for C3 grasses (Fischer et al., 2008; Willmott et al., 2001). In addition, the seasonality of the rainfall have also a greater impact on the distribution of C3 and C4 grasses over Chad. The summer monsoon rainfall along with the higher temperature favors the growth of C4 grasses, whereas the wintertime rainfall increases the C3 grass cover (Fischer et al., 2008; Ode et al., 1980; Polley et al., 2014; Skinner et al., 2002). The seasonality of rainfall seems to have a greater impact over the C3/C4 grass distribution (Fig. 4a–b). For example, the north hemispheric winter over Chad is normally devoid of rainfall hence it does not support the growth of the C3 plants. This

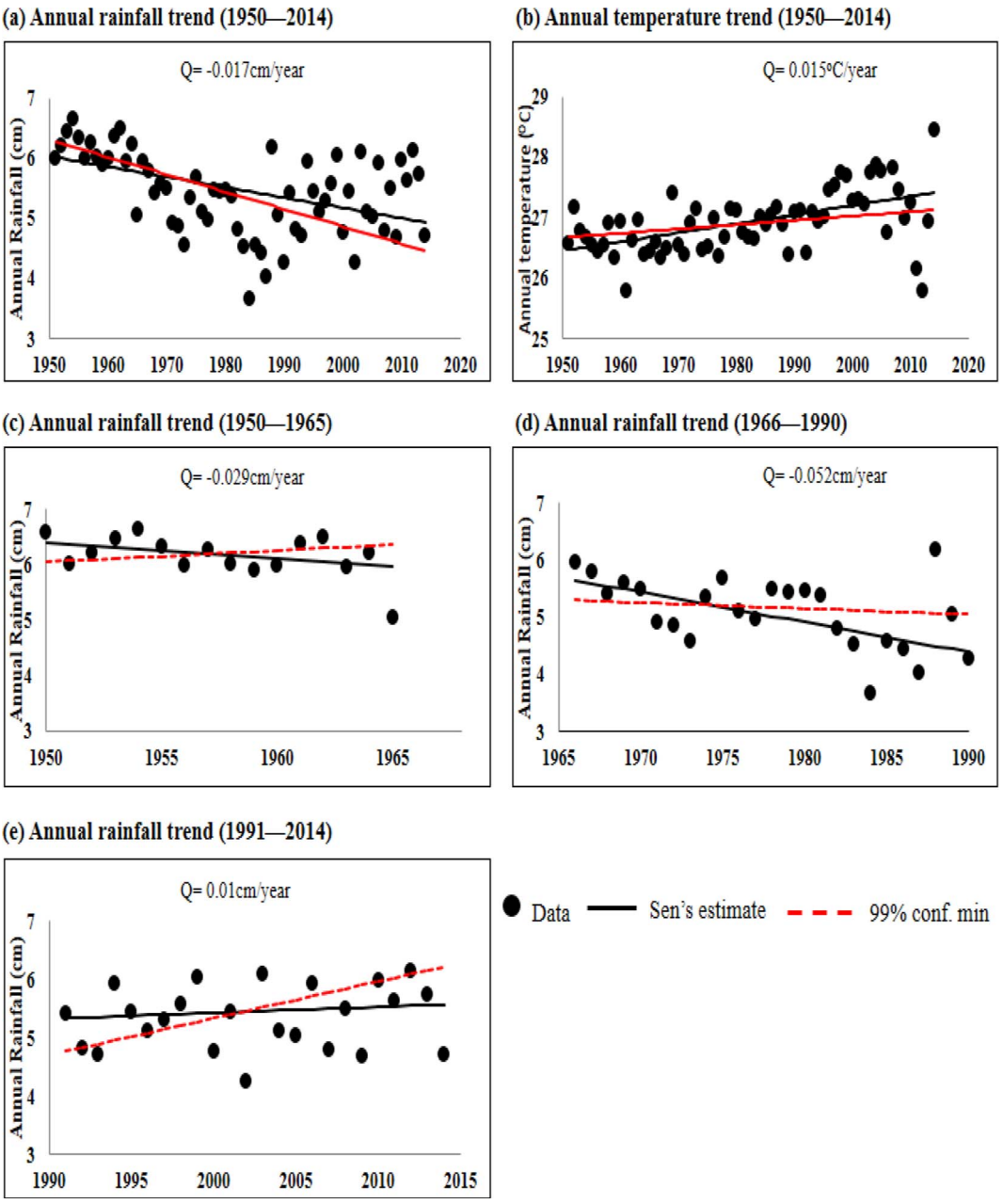

Fig. 6. Annual (a) rainfall and (b) temperature trend over Chad (showing Sens estimated trend at 99% level of significance) for the period 1950–2014. Similar annual rainfall trend but for the period (c) 1950–1965, (d) 1966–1990 and (e) 1991–2014.

results in very thin cover of C3 grass cover over Chad (0 to 30%); while the maximum thickness is observed just south along the Sahara Desert margin (70 to 80%) around 14° N to 16° N(Fig. 4a). Chad receives most of its rainfall during JJA; in addition, it is also the hottest season of the year. The arid climate prevailing over Chad, along with the monsoon precipitation and higher temperature become favorable for the growth of C4 grasses. Hence, the C4 grass cover is much thicker on the southern Chad (70 to 90%) in a latitude band ranging from 7° N to 14° N(Fig. 4b). Chad has a thin layer of shrub cover land just south of the margin of Sahara Desert (Fig. 4c) in almost same latitudinal range where C3 plants are predominant. From this distribution, it can be inferred that the shrubs are mostly consist of C3 plants. The area under Sahara Desert is devoid of rainfall during most time of the year and does not support vegetation, hence the bare lands are predominant over north Chad above 16° N.

4.2. Interannual variability

The interannual variability of temperature and precipitation over Chad for all the seasons as well as annual mean are analyzed in terms of the standardized anomalies (Fig. 5a–e). The interannual variability of rainfall during DJF shows that there is an increasing trend in the rainfall from 1995 onwards (Fig. 5a). Generally, rainfall does not occur over the Chad during DJF, so the occasional shower resulted in the sudden rise of the standard deviation from 1995. The standard deviation of temperature is 0.8 °C. In most of the years, the standardized anomaly of temperature value lies mostly between +1 and −1 that implies most of the averaged DJF temperature lies in the normal temperature range.

The standard deviation of rainfall during MAM is 0.78 mm/day. Four excess rainfall years are recorded with standardized anomaly greater than +2 between 1950 and 1965, and only one excess year is

Table 1
Seasonal and monthly rainfall trend statistics.

	Periods	1950–2014			1950–1965			1966–1990			1991–2014		
		Z statistics	Level of significance	Q value (cm/year)	**Z statistics**	Level of significance	Q value (cm/year)	**Z statistics**	Level of significance	Q value (cm/year)	**Z statistics**	Level of significance	Q value (cm/year)
Seasons	DJF	0.50		0	−0.99		−0.010	0.12		0.000	2.26	**0.1**	0.010
	MAM	−1.63		−0.022	−0.99		−0.109	−1.70	**0.1**	**-0.094**	−0.87		−0.071
	JJA	−3.67	**0.001**	**-0.147**	0.10		0.032	−2.22	**0.01**	**-0.319**	0.62		0.099
	SON	−1.38		−0.030	−1.68	**0.1**	**-0.329**	−1.80	**0.1**	**-0.138**	0.87		0.062
Months	January	1.37		0.0	0.99		0.000	−0.02		0.000	−0.47		0.000
	February	0.24		0.0	−1.39		−0.007	−1.05		−0.001	1.96	**0.1**	**0.005**
	March	−2.55	**0.05**	**-0.005**	−1.48		−0.020	−0.21		−0.001	0.57		0.005
	April	−2.24	**0.05**	**-0.013**	2.08	**0.01**	**0.095**	−4.04	**0.001**	**-0.070**	−1.36		−0.039
	May	−0.24		−0.022	−2.28	**0.01**	**-0.204**	−0.35		−0.016	−0.17		−0.008
	June	−2.05	**0.05**	**-0.021**	0.79		0.098	0.44		0.020	0.67		0.023
	July	−1.43		−0.030	0.00		0.003	0.49		0.026	0.92		0.101
	August	−3.10	**0.01**	**-0.074**	0.00		−0.029	−2.45	**0.01**	**-0.260**	0.42		0.047
	September	−2.077	**0.05**	**-0.036**	−1.78	**0.1**	**-0.255**	−2.08	**0.01**	**-0.130**	0.47		0.044
	October	0.11		0.001	−1.19		−0.088	−1.28		−0.038	0.57		0.028
	November	0.86		0.001	−0.20		−0.003	−0.12		0.000	0.17		0.002
	December	−0.57		0.0	0.69		0.000	0.02		0.000	0.72		0.000

Table 2
Seasonal and monthly temperature trend statistics.

	Periods	1950–2014		
		Z statistics	Level of significance	Q value (cm/year)
Seasons	DJF	1.30		0.008
	MAM	4.08	**0.001**	**0.022**
	JJA	4.80	**0.001**	**0.019**
	SON	2.73	**0.01**	**0.014**
Months	January	0.45		0.004
	February	1.13		0.011
	March	1.91	**0.05**	**0.013**
	April	4.32	**0.001**	**0.026**
	May	4.01	**0.001**	**0.022**
	June	4.48	**0.001**	**0.021**
	July	3.74	**0.001**	**0.016**
	August	3.69	**0.001**	**0.018**
	September	3.48	**0.001**	**0.016**
	October	1.74	**0.05**	**0.009**
	November	1.59		0.013
	December	1.37		0.011

recorded during 1991 between 1966 and 2002 (Fig. 5b). Few deficit rainfall seasons are observed after 1980 and rainfall tends to decrease later on. The MAM standard deviation value of temperature is around 0.7 °C. The standardized temperature anomalies have an interesting pattern and increasing from 1950 to 2002. Initially the standardized anomalies are in negative side till 1976 and afterwards it become positive till the end of study period indicating a gradual warming during MAM.

As discussed in the climatology section (Section 4.1) the majority of rainfall over Chad occurs during the monsoon months (JJA). From 1950 to 1960, there are some years with standardized anomaly greater than +1 that implies heavy rainfall during monsoon season (wet period). Afterwards, the standardized anomaly value decrease till 1984 (dry period) where it reaches below −2(Fig. 5c). This result is in agreement with the earlier studies (Funk et al., 2012; Giannini et al., 2008; Hulme et al., 2001; Kandji et al., 2006), which have reported the state of desiccation over Sahel region from early part of 1960 till 1990 and the driest reported years are 1983 to 1985. Afterwards it increase again from 1990 onwards (Hulme et al., 2001; Nicholson et al., 1997) but still most of the seasons are rainfall deficit (recovery period). One of the earlier study (Nicholson et al., 1997) also support our finding which depicted the decreasing rainfall trend till 1970s and positive rainfall trend after 1990s over Chad. The standard deviation of temperature value during monsoon is 0.57 °C. The standardized anomaly of temperature increases from 1950 to 2014. Most of the summers are cold (the climatological temperature is below average) between 1950 and 1962 and the warm monsoon seasons are experienced between 1995 and 2014. The middle period is the transition period from colder to warmer summer.

SON is the second highest precipitating season over Chad. The reported standard deviation of rainfall is 1.1 mm/day (Fig. 5d). The seasonal standardized anomaly decrease from 1950 to 1985 and afterwards it regains its momentum. Most of the SON seasons are either excess or deficit. The standard deviation of temperature is around 0.64 °C during SON. Most of the seasons between 1950 and 1970 are cold, the seasonal temperature rises gradually, and it becomes mostly warm after 1990.

The annual standard deviation value of precipitation and temperature are 0.2 mm/day and 0.51 °C respectively (Fig. 5e). Since JJA contributes majority of the annual rainfall, the annual rainfall curve follows similar path like JJA rainfall curve, where excess rainfall years are experienced between 1950 to 1962. The time series suggest that the rainfall anomaly was greater than 2 standard deviation in most of the years during 1950 to 1965 and less than 1 standard deviation during 1966 and 1990; while, the lowest standardized anomaly (driest summer) reported in 1984. The rainfall again increases from 1985 to 2014 but most of the years lie on the drier side. The analysis shows a rise of temperature from 1950 to 2014 (Heinrigs and Trémolières, 2012) and the increasing is more prominent between 1990 and 2014 (I. P. on Climate Change, 2015). Few cold years (lower standardized anomaly value) are observed between 1950 and 1965, while most of the year lies in the normal temperature category between 1966 to 1995 and afterwards warm years has been observed from 1996 onwards till 2014.

4.3. Climatic trends

In this section, the annual trend of temperature and precipitation are analyzed using non-parametric MK-test. It is used to detect the monotonic trends and have been used in several earlier studies (e.g. Alexander et al., 2006; Westra et al., 2013; Tan and Gan, 2015) to estimate trends in time series of annual values of temperature and precipitation. The positive Z- value corresponds to the increasing trend while its negative value corresponds to decreasing trend. The rate of the increasing/decreasing trend is computed using Sen's slope.

The annual trends of rainfall and temperature using MK-test are shown in Fig. 6a–b, while the seasonal and monthly trends have been

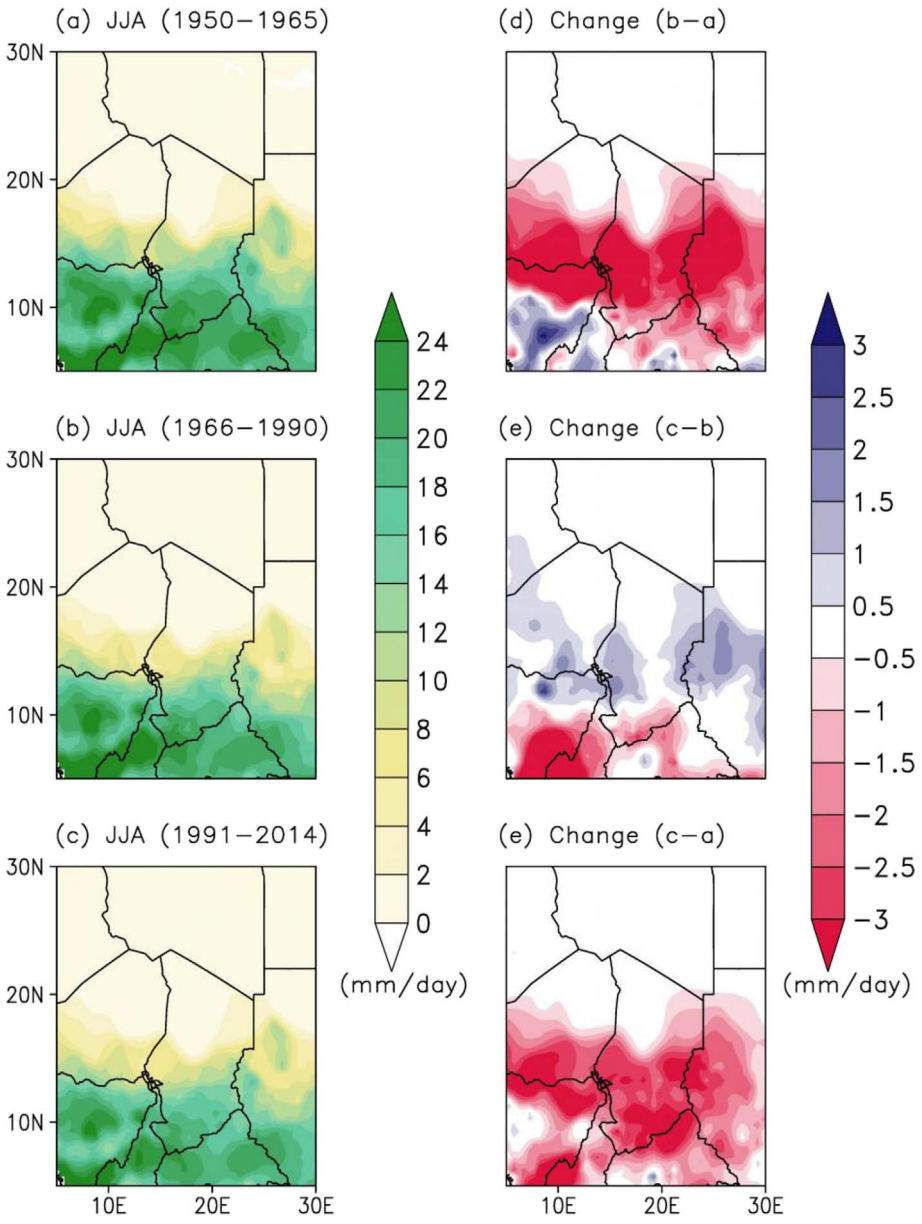

Fig. 7. Climatological JJA rainfall (mm/day) obtained from UDEL for the period (a) 1950–1965, (b) 1966–1990 and (c) 1991–2014 and (d–f) their difference.

represented in Table 1. The overall trend of annual rainfall shows a statistically significant decreasing trend over Chad for the whole period (1950 to 2014). The rate of decrease is computed using Sens slope method is found to be 0.17 mm/year (Fig. 6a). Further seasonal and monthly rainfall trend analyses have been carried out to identify the contribution of individual season and month towards better understanding of the trends. The rainfall shows an increasing trend during winter (DJF) while it is decreasing for rest of the seasons (Table 1). The rate of decrease is highest for monsoon season (JJA). The majority of rainfall occurs during monsoon and it contributes maximum to the total annual rainfall, hence the decrease in JJA rainfall trend can also be reflected in annual rainfall trend. The rate of decrease of rainfall is 1.47 mm/year during JJA and is significant at 0.01 confidence level (Table 1). Similarly, the monthly rainfall analysis reflects a decreasing trend during most of the months except for January and November. The rate of decrease of rainfall is significant during summer months and the magnitudes are 0.21, 0.3 and 0.74 mm/year for June, July and August respectively.

The annual temperature shows an increasing trend of 0.015 °C /year at 0.01 significant level during 1950 to 2014 (Fig. 6b). Positive temperature trend is observed during all seasons; where, the highest magnitude is observed during summer followed by pre-monsoon and post-monsoon (Table 2). The rate of increase of temperature are statistically significant during pre-monsoon, summer and post-monsoon are 0.022, 0.019 and 0.014 °C /year respectively (Table 2). All the months are showing increasing temperature trends over Chad (Table 2). The months from April to September (pre-monsoon and summer months) show a statistically significant rate of increase of 0.26, 0.022, 0.021, 0.016, 0.018 and 0.016 °C /year respectively. The increasing trend is highest for April among all the months.

4.4. Observed climate change in three sub-periods

The careful analysis of inter-annual variability in the earlier section clearly shows that the rainfall initially have higher magnitude (6 to7 cm/year) during 1950 to 1965 with a slight decreasing trend of 0.29 mm/year (Fig. 6c). This period with higher magnitude of rainfall (wet period) over Sahel is also documented by earlier studies (Nicholson, 2000). The rainfall during the two decades (1970s and 1980s) experience drastic decrease in rainfall over Sahel and hence the

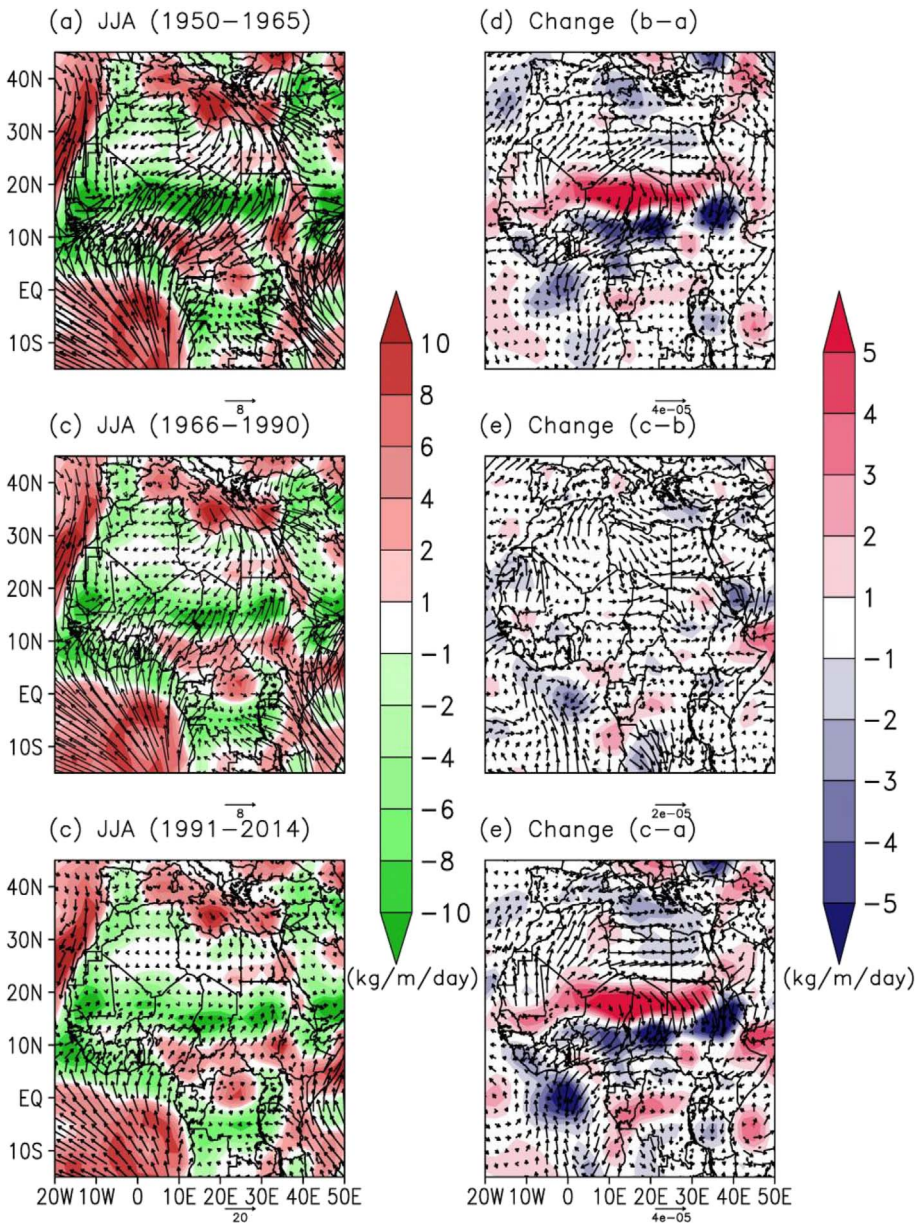

Fig. 8. Climatological JJA vertical integrated moisture flux $\times 10^{-5}$ (kg/m/day: shaded) and transport (vector) obtained from NCEP/NCAR reanalysis for the period (a) 1950–1965, (b) 1966–1990 and (c) 1991–2014 and (d–f) their difference.

drought frequency increases during this period (Le Barbé et al., 2002; Nicholson, 2000; Thorncroft et al., 2011). The rainfall during this period decreases by 25% as compared to the earlier decades. The decrease of rainfall during 1983 and 1984 leads to continent wide drought and 1984 is found to be the driest year (Hulme et al., 2001) since 1950 till present. The present analysis also supports the decreasing trend of rainfall over Chad from early 1960s at a higher rate (0.52 mm/year) till 1990 (Fig. 6d) and considered this period as dry period for further analysis. Literature shows that the Sahel region enters a humid regime after 1990s and hence the rainfall increases. The increase in the rainfall after 1990 may be attributed to the increase in deep convection more northwestward over Africa along with the shift of Saharan heat low (Thorncroft et al., 2011). In agreement with the earlier studies, the present analysis also shows an increasing rainfall trend at a rate of 0.1 mm/year from 1990 till 2014 over Chad (Fig. 6e). So during this period, the rainfall over Chad starts to recover and now it is moving from dry regime towards wet regime. This revival of rainfall during last three decades is very encouraging for Chad. So following the tendency of the rainfall magnitude and trend, the entire period of study has been divided in to three distinct sub-periods for the further analysis, such as wet period (1950 to 1965), dry period (1966 to 1990) and recovery period (1991 to 2014).

The seasonal trend analysis of the wet period (1950 to 1965) shows an increase of rainfall during JJA at a rate of 0.32 mm/year; while other seasons are showing decreasing rainfall trend (Table 1). During the dry phase (1966 to 1990), all the seasons show statistically significant decrease in rainfall trend except DJF. The rate of decrease for MAM, JJA and SON are 0.94, 3.19 and 1.38 mm/year respectively. Since rainfall does not occur over Chad during DJF, it is not showing any statistically significant trend (Table 1). During the revival phase (1991 to 2014), the increasing rainfall trends are observed for DJF, JJA and SON with a rate of 0.1, 0.99 and 0.62 mm/year respectively.

The monsoon months during the wet period (1950 to 1965) show no significant rainfall trend (Table 1). However, the rainfall during January, April, June and December show increasing trend while rest of the month exhibits decreasing trend. The rainfall during dry period shows negative trend for all the months except June and July (Table 1). The significant decrease of rainfall during August may result in the drying of JJA during dry period. During the revival period, the rainfall trend increase for most of the months. The rate of increase of rainfall during

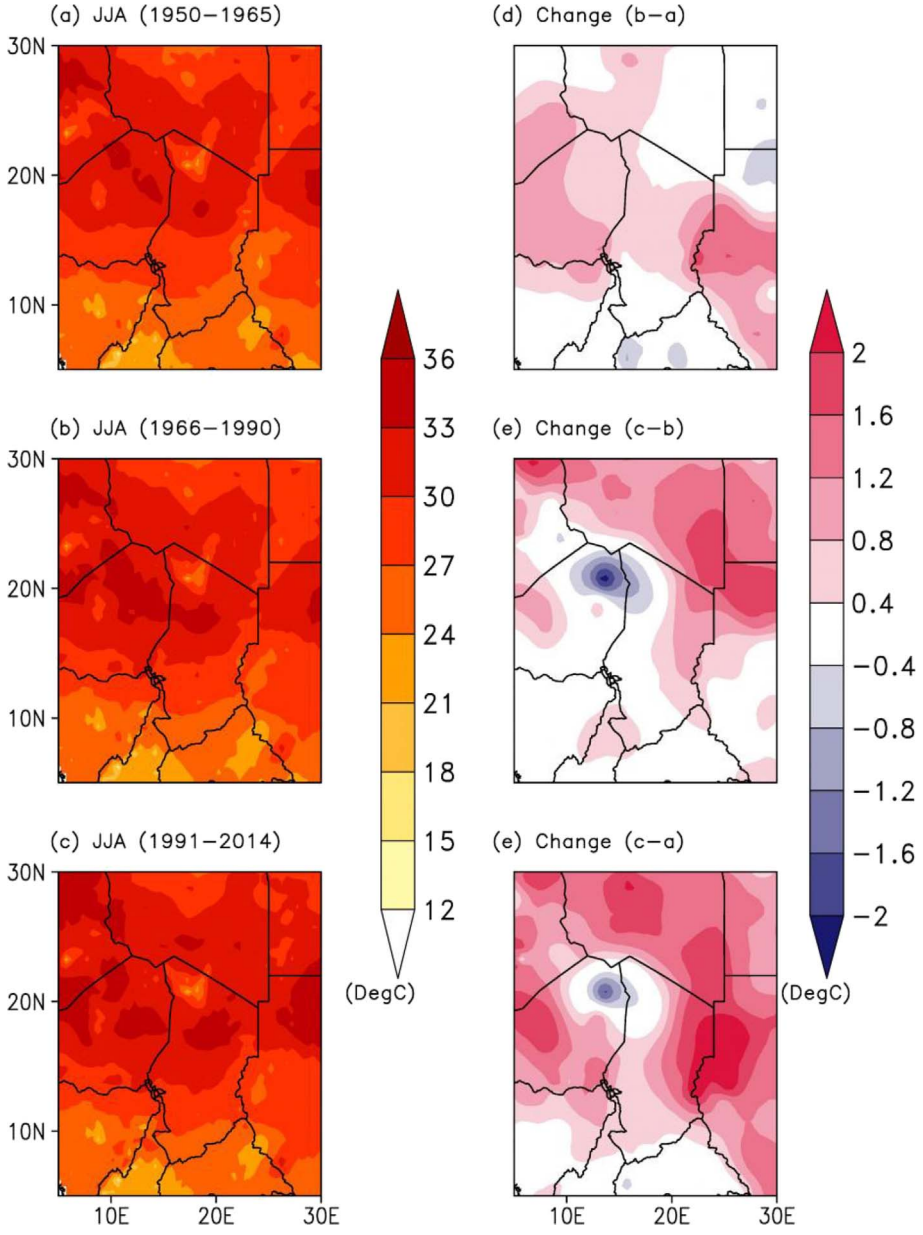

Fig. 9. Climatological JJA 2 m air temperature (°C) obtained from UDEL for the period (a) 1950–1965, (b) 1966–1990 and (c) 1991–2014 and (d–f) their difference.

June, July and August are 0.23, 1.01 and 0.47 mm/year respectively. Further, observed changes during these three sub-periods are further examined by the analysis of rainfall along with moisture flux transport and divergence, temperature and the change in vegetation pattern.

Fig. 7a–f depicts the climatological JJA rainfall for these three sub-periods and their differences. The climatological rainfall during the wet period is higher and the rainfall of around 14mm/day can be observed up to 18° N latitude over Chad (Fig. 7a). While during dry period, the rainfall decreases drastically over central Chad (which is a part of Sahel) and rainfall band of 14 mm /day confined within 12° N latitude (Fig. 7b). During the recovery period, the rainfall slowly starts to increase on the higher latitudes over Chad (Fig. 7c). The climatological rainfall for JJA during wet, dry and recovery periods are 16.1, 13.3 and 13.5 mm/day respectively. The difference between the dry and wet period shows a drying of the more than 3 mm /day over Chad (Fig. 7d). This indicates severe deficit of the rainfall during dry period. The difference of rainfall climatology between revival and dry period shows increase of the rainfall over 10° N up to 18° N by 1 to 2.5 mm/day (Fig. 7e). The difference of rainfall climatology between recovery period and wet period also shows drying over the central and south Chad (Fig. 7f). The rainfall magnitude significantly decreases during the dry period, but the rate of recovery is very slow hence climatological rainfall value have not increased much. This is the reason for dry bias over Chad when it is compared with the wet period. Similar finding are also reported from the analysis of CRU and GPCC rainfall dataset (Supplementary Figs. 5–6).

The vertically integrated moisture flux and transport and its relationship with the rainfall is further analyzed for the three sub-periods (Fig. 8). The wet period show stronger moisture divergence (convergence) from Atlantic Ocean (central Chad); this stronger divergence of moisture towards Chad causes heavy rainfall, which extends up to 18° N(Fig. 8a). During dry period, the weakening of the divergence (convergence) of moisture from ocean (towards central Chad) is evident, which results in decrease of rainfall over Chad (Fig. 8b). The moisture convergence start to increase during revival phase (Fig. 8c) and the rainfall starts to peak gradually. The difference of moisture flux and transport between the dry and wet period shows negative value over central Chad indicating stronger convergence during wet period (Fig. 8d); similar finding are also observed for difference between recovery period and wet period (Fig. 8f). The smaller positive value of the

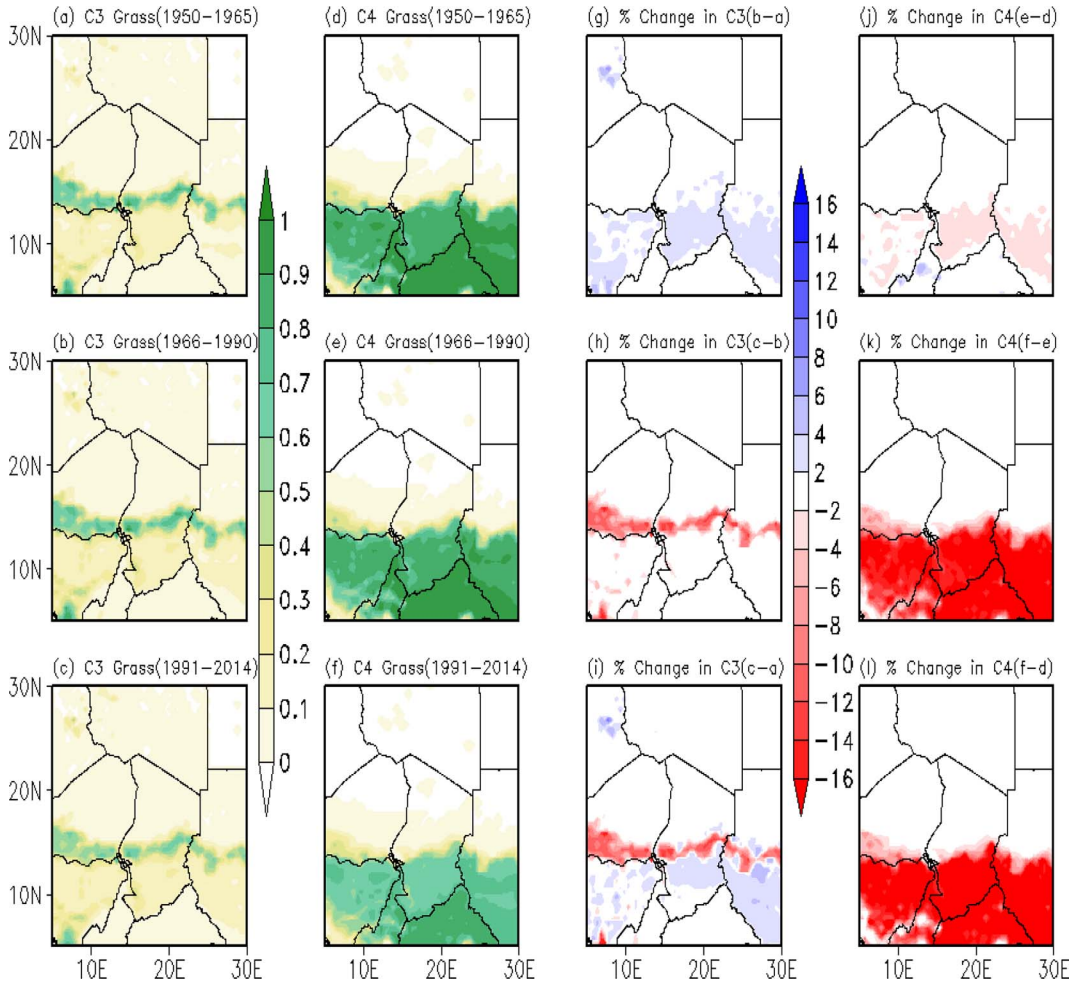

Fig. 10. Climatological distribution of C3 and C4 grass over Chad for the period 1950–1965, 1966–1990 and 1991–2014 (a–f) and their respective percentage change (g–l).

difference between revival and dry period indicates the slight increase in the convergence tends to increase the rainfall during revival phase (Fig. 8e).

The JJA temperature climatology during these three sub-periods show similar spatial structure of temperature (Fig. 9a–c); but the magnitude tends to increase with time. The temperature trend shows an increasing rate of 0.015 °C /year during the entire period. Therefore, the temperature gradually increase from wet to dry to recovery period. The difference of climatological temperature between dry and wet period (Fig. 9d) and recovery and dry period (Fig. 9e) show increase of temperature over entire Chad by 0.5 °C to 1 °C. While, the difference of temperature between recovery and wet period reflects a higher rise of temperature ranging from 0.5 °C to 2 °C(Fig. 9f) over Chad except for few part of north-west Chad. Similar results are also found for CRU and NCEP datasets (Supplementary Figs. 7–8).

The changes in different type of landcover (such as C3 grass, C4 grass, shrubs and bareland) during these three sub-periods are directly linked to the change in temperature as well as precipitation pattern. The climatological distribution of C4 and C3 plants is provided for three sub-periods along with their difference (Fig. 10a-l). The difference (dry minus wet) period shows decrease of the C4 grass cover over central and southern Chad. This may be attributed to the decrease in the monsoonal precipitation, which is very helpful for the growth of C4 grasses (Ehleringer, 2005; Warne et al., 2010; Winslow et al., 2003). Although, the rainfall revival takes place during later phase but the rate is very slow which probably may not very helpful enough for the C4 grass cover. Hence, this shows decrease of the C4 plant cover during revival phase with respect to wet and dry period (Fig. 10k–l).

The climatological C3 grass cover for the three sub-period are represented (Fig. 10a–c). The decrease of summer rain during dry period reduce the C4 plant cover as a result the C3 grass cover tends to increase, as they always compete with each other (Sage and Monson, 1998). This is evident from the difference plot of C3 grass cover between dry and wet period (Fig. 10g). The comparison of revival period and dry period (revival minus wet) shows decrease of C3 grass cover (10%) just south of Sahara in a band like structure (Fig. 10h). This decrease may be attributed to the gradual increase of temperature particularly over central Saharan region, which is around 35 °C or more. The optimum temperature range for the growth of C3 grasses is from 18 °C to 20 °C (Fischer et al., 2008). The temperature rise over central Chad reduce the C3 grass cover (Red band: 10%); while the drying of monsoon reduce the C4 grasses and C3 grasses complete and grow (5%) in the southern part of Chad (Fig. 10i). The analysis of shrub percentage does not show much change from wet to dry period (Supplementary Fig. 9a–f) but a sudden decrease during revival period. This may be due to the effect prolonged dry period followed by revival period (where rainfall trend to increase at a very slow rate), which reflect at a later stage (Supplementary Fig. 9c). Therefore, the shrub shows a decrease of 8 to 12% along the southern margin of Sahara Desert. Similarly, bare land change is almost miniscule during the transition from wet to dry period (Supplementary Fig. 10). The rainfall increase during revival phase may helps to reduce the bare land (15%) particularly over Sahara, which is evident from the difference plots between revival period and wet/dry period (Supplementary Fig. 10e–f).

5. Summary and conclusions

The climate variability over a central-north African country " Chad" is examined using different reanalysis datasets in terms of temperature and rainfall from 1950 to 2014. It also considers the effect variability on the LULC over Chad. It is found that most of the rainfall over Chad occurs during JJA and hence is the major contributing season towards the total annual rainfall. The moisture flux and transport shows that during JJA, the transport of moisture take place from Atlantic Ocean as well as from Mediterranean Sea and its convergence places place over central and southern part of Chad respectively, which leads to higher rainfall. JJA is the hottest season over Chad. The analysis of standardized anomaly depicts the increase of temperature from 1950 to 2014. The annual rainfall trend is slightly decrease but the rainfall amount were high from 1950 to 1965 (Wet period); decreased from 1966 to 1999 (Dry period) and then again increases at a smaller rate from 1991 to 2014 (Recovery period).

The annual rainfall trend shows a decrease of 0.17 mm/year for the entire study period (1950 to 2014). The seasonal analysis reflects the highest rate of decrease during JJA (1.47 mm/year). In addition, the rate of decrease is very high during August (0.74 mm/year) among the monsoon months. The decrease of rainfall in a country like Chad, which is close to the Sahara, may have devastating influence in future and hence water management and conservation plans are of utmost importance in this region. The analysis of rainfall shows a decreasing trend during wet phase (29 mm /year), the rate of decrease become higher during dry phase (52 mm /year) while it starts to increase very slowly (1 mm /year) during the revival phase. The statistically significant decrease of rainfall during MAM, JJA and SON in the dry period leads to several cases of occurrence of drought (Le Barbé et al., 2002; Nicholson, 2000; Thorncroft et al., 2011). The climatological rainfall for JJA during wet, dry and recovery periods are 16.1, 13.3 and 13.5 mm/day respectively. The spatial extension of the convergence over Chad during wet phase is towards more north, which gradually shifted a little south in dry phase. Whereas in revival phase, the convergence over Chad starts to increase slowly again. The annual temperature shows an increasing trend of 0.015 °C and the seasonal temperature shows higher rate of increase during summer (0.019 °C /year). The rate of increase of temperature is highest during April (0.022 °C /year) among months. The constant increase of the temperature clearly indicates that the revival period is the warmest and the wet period is the coolest over Chad.

The C3 as well as C4 plants are very sensitive to the temperature as well as the seasonal precipitation. Since the C4 plants are very sensitive to the JJA rainfall, the decrease of rainfall during dry period reduced the C4 plant cover (Ehleringer, 2005; Warne et al., 2010; Winslow et al., 2003). The decreased annual rainfall and slow increasing rate of rainfall during revival period may not sufficient for expansion of C4 grass cover. The decrease of C4 plant cover during dry phase helps to increase the C3 grass cover because they are competing with each other (Sage and Monson, 1998). The temperature rise over central Chad reduce the C3 grass cover just south of Sahara Desert during revival period whereas the drying of monsoon reduce the C4 grasses and increase C3 grasses in the southern part of Chad. The lesser magnitude of rainfall during dry and revival period may result in this decrease of shrub cover over Chad. While the rainfall revival during the later phase has reduces the percentage of bare land over Sahara. The major limitation of this study is the lack of long-term observed meteorological data over Chad, so this study primarily focuses to use difference climate reanalysis. In the future work, the trend analysis of rainfall and temperature will be examined more comprehensibly over the major cities of Chad.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2018.01.013.

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